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PRESSURE-SENSITIVE PAINT MEASUREMENTS ON A ROTOR DISK SURFACE AT HIGH SPEEDS

by
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PRESSURE-SENSITIVE PAINT MEASUREMENTS ON A ROTOR DISK SURFACE AT HIGH SPEEDS

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ABSTRACT

Measurement of the static-pressure distribution over the surface of a rotor disk was attempted using pressure-sensitive paint (PSP). A uniform-stress, high-speed rotor disk, fitted with a shock generator, was built, installed and operated at speeds in excess of 20,000 RPM by a Hamilton-Standard turbine-driven fuel pump. A once-per-revolution trigger signal was converted to a transistor-to-transistor logic (TTL) format and used to gate an intensified charged-coupled device (CCD) video camera. Multiple low-intensity-level camera exposures were integrated and captured to produce a single usable image. Ten captured images were averaged to increase the image's signal-to-noise ratio and the result was used to produce an image ratio with respect to a static reference condition. Finally, a pseudo-coloring process was used to develop a color image that related intensities to both temperature and pressure distributions in accordance with the Stern-Volmer relation. Paint stripping and temperature dependence prevented the measurement of pressure at transonic speeds. The test-bed facility and acquisition techniques developed here could now be used to overcome those limitations.

TABLE OF CONTENTS

I. INTRODUCTION

Recent developments in the use of luminescent coatings on turbomachinery blading as a means for measuring spatial distributions of blade surface pressure and temperature has generated significant interest. Current methods for obtaining surface pressure measurements require the installation of individual pressure ports along each aerodynamic surface. Although highly accurate, the information is spatially discrete and is usually not cost effective for rotor blade analysis (due to the complex array of pressure lines that must be installed and led out of a "pressure-instrumented" model) [Refs. 1-10]. Pressure-sensitive paints (PSP); however, offer a conceptually simple means for determining continuous blade surface pressure distributions. Such information is critical in the validation of new rotor designs that are based on computational fluid dynamic (CFD) calculations.

Originally applied to high pressure gradient external flows (supersonic and transonic), the wide application of PSP's as a quantitative measurement tool has been slowed as a result of the strong/moderate temperature dependence of the active probe molecule and associated chemical binder. PSP's temperature dependencies have been cited as the reason for errors in measuring correct surface pressure when compared with conventional pressure taps and probe measurements. Attempts to calibrate these temperature effects and to incorporate the results to produce comparable surface pressure measurements with conventional methods is the subject of on-going research.

The present study continues the work done by Sievwright, Varner, and Quinn at the Naval Postgraduate School (NPS) to develop the means and capability to produce quantitative, temperature-corrected, PSP measurements of surface pressure distributions on high-speed rotors [Refs. 1-3]. The PSP test bed built by Varner [Ref. 2] and further developed by Quinn [Ref. 3] was used. A 12-inch diameter, aluminum, uniform-stress, rotor disk, with small shock generators inserted near the rim was designed, built, installed, and operated at transonic tip speeds (>20,000 RPM). PSP was applied locally in the area where significant surface pressure gradients, as a result of the generation of shock waves, would exist. Images, measuring local luminescent intensities, were captured using EPIX 4MIP frame-grabber software. The image intensity distribution over the PSP was then interpreted to determine variations in surface pressure and surface temperature using the Stern-Volmer relationship.

The following section briefly describes the concept and application of pressure sensitive paints and the governing relationships between pressure and luminescence. Section III gives a brief description of the image acquisition systems developed to capture pressure distribution images. Section IV describes the test methodology, while Sections V and VI discusses the results and conclusions and provide recommendations for further analysis.

II. THEORY OF PRESSURE-SENSITIVE PAINT

PSP uses a photoluminescence and oxygen-quenching process by which the molecular energy state of an active molecule, excited by radiation from its ground energy state, S_0, to a higher energy state, S_i ($I > 2$), returns to its original state through a series of naturally occurring processes. A molecular internal conversion process instantaneously (10^{-9} - 10^{-12} secs) converts the molecule to its lowest excited state, S_1. The molecule is then returned to its ground state through the emission of light, or via a radiationless process. Oxygen quenching is one radiationless process in which the transfer of energy is the result of molecular interactions (collisions) with an oxygen molecule. As a result, the partial pressure of oxygen that is diffused in a PSP paint layer medium is inversely proportional to the amount of emitted radiation [Ref. 1 and 11]. Since the mole fraction of oxygen in air is 0.21, as the air pressure over the paint surface is increased, more oxygen molecules are diffused and interact with the PSP, resulting in increased oxygen quenching and less radiation emittance from the PSP. The oxygen-quenching process has been modelled by the Stern-Volmer relation,

$$\frac{I_o}{I} = A(T) + B(T)\frac{P}{P_o} \qquad (1)$$

where I_o and P_o are the reference luminescent intensity and reference pressure, respectively, and I and P are measured intensity and pressure at the experimental conditions. The coefficients A and B are derived from calibration data and generally are temperature dependent. In the present study, the reference intensity and pressures were measured at ambient static conditions (e.g. wind-off) and experimental conditions (wind-

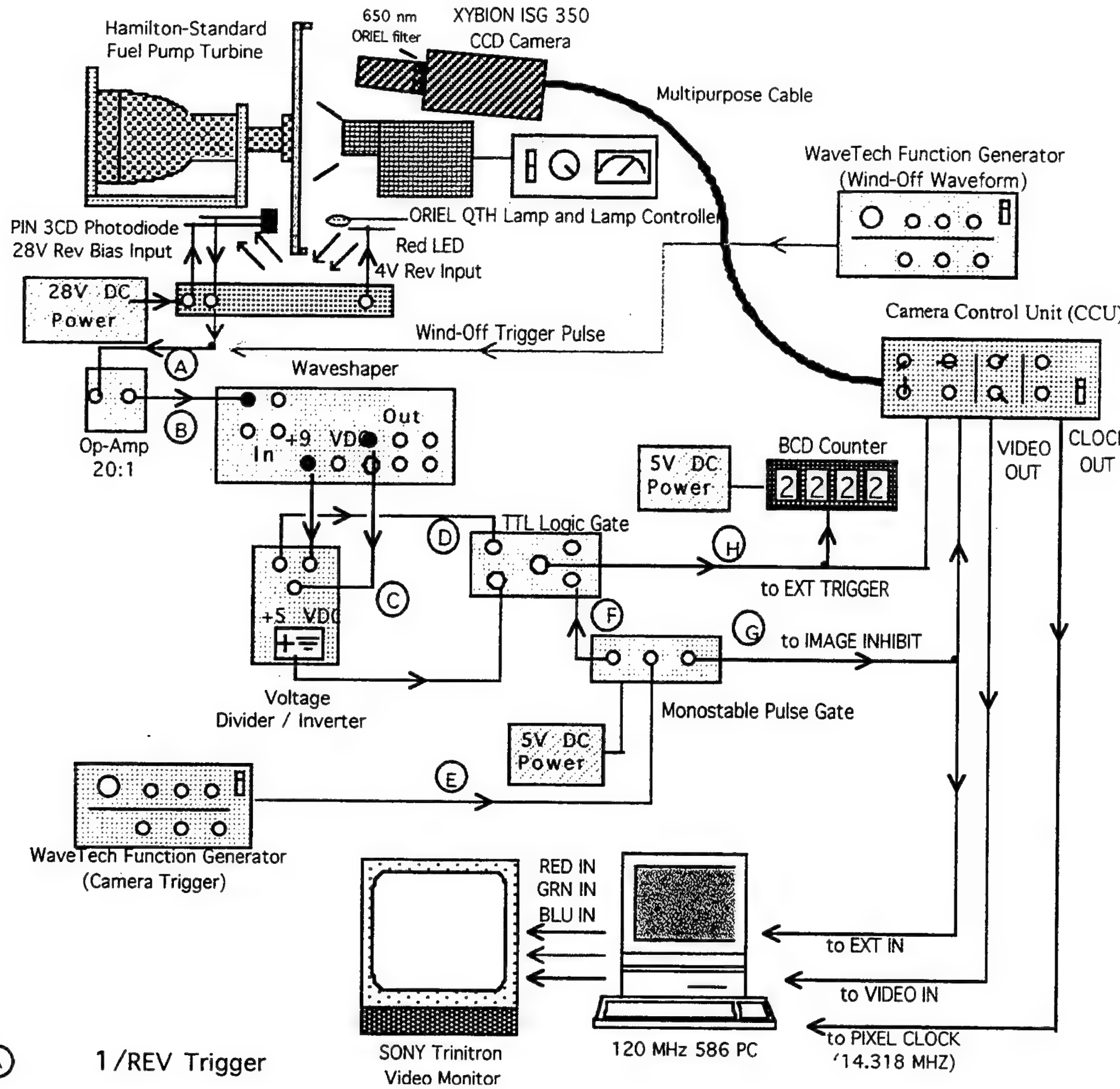
on) were measured using a phase-locked acquisition technique at various rotor speeds. The PSP used in the present work was composed of Platinum Octaethyl Porphyrin (PtEOP) as the active molecule dissolved in an oxygen-permeable binder, GP-197 [Ref. 10]. The active molecule was excited at an absorption peak of 380nm and photoluminescence occurred at 650 nm, corresponding to the colors of violet and red, respectively, in the visible light spectrum.

III. PSP MEASUREMENT APPARATUS

A PSP test-bed facility at the Naval Postgraduate School's Gas Dynamics Laboratory was used for the present study. A schematic of the facility and image-acquisition system is shown in Figure 1. An aluminium rotor disk mounted on a turbine drive for a fuel pump was enclosed in an open-ended cylindrical steel spin chamber. The image acquisition system consisted of a RPM counter, CCD camera, camera control unit (CCU), Oriel illumination system, EPIX frame-grabber software, and associated hardware and software devices required to capture and store "freeze frame" images of a pressure event generated by a shock generator on the rim of a disk moving at supersonic speeds. Varner and Quinn [Refs. 2 and 3] provided detailed descriptions of the test facility and PSP test-bed set up. The following provides a brief description of the PSP test-bed facility components and the modifications made during the course of the present work.

A. ROTOR DISK

A 12-inch diameter, aluminium, rotor disk, designed for uniform stress and machined at NPS, was used as the PSP experimental platform. Figure 2 shows the rotor disk dimensions and Figure 3 shows the rotor as it was mounted on the turbine-driven shaft. High centrifugal stress loading was the prime design consideration and led to the rotor's tapered profile. Two ¼-inch stainless steel Allen set screws were machined and set 180° apart at a radial distance of 5.8 inches from the rotor center. The set screws, extended 3/32 inches above the rotor face, were intended to act as shock generators at



(A) 1/REV Trigger

(B) Amplified 1/REV Trigger

(C) 9V Active Low 1/REV

(D) 5V High TTL 1/REV

(E) 5V Trigger Pulse

(F) (G) 5V Active High Monostable Pulses

(H) 5V Low TTL Signal

Figure 1. Image Acquisition System

Source: Quinn, K. J., "Pressure-Sensitive Paint Measurement Technique Development for Turbomachinery Application," M.S. Thesis, Naval Postgraduate School, Monterey, California.

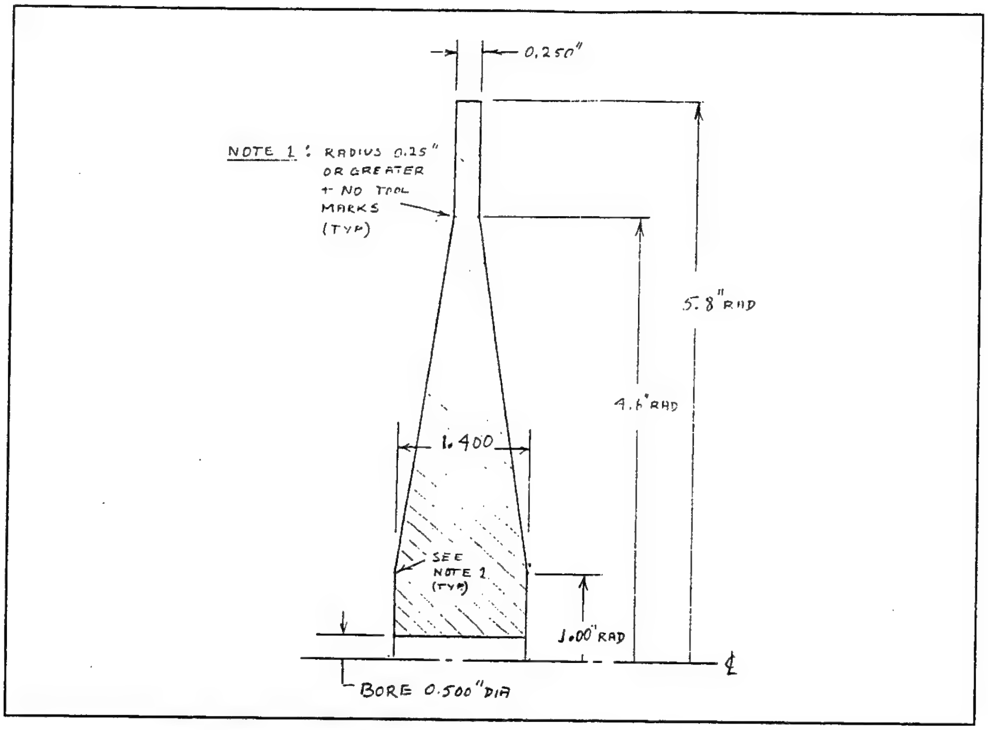


Figure 2. Rotor Disk Dimensions

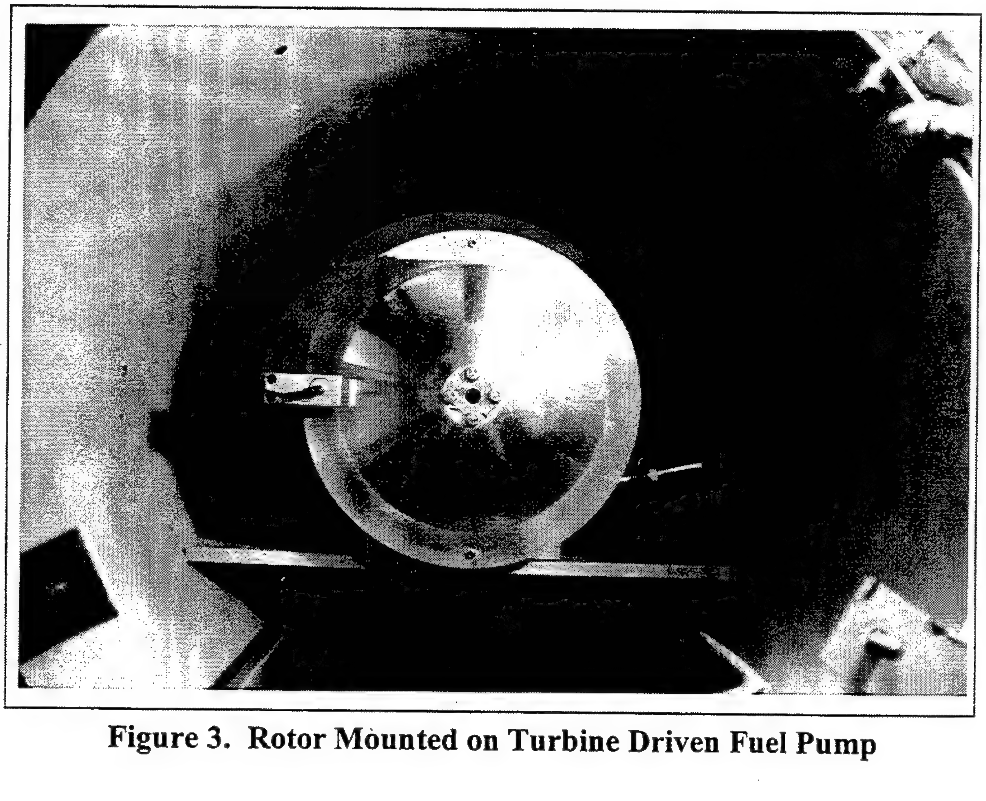


Figure 3. Rotor Mounted on Turbine Driven Fuel Pump

supersonic rotor speeds. Two 1/8-inch holes were located 5.8 inches radially from the rotor center. One hole was used, with an optical system, as a RPM pick-up point, and the other was partially filled with a non-transparent epoxy. The rotor assembly (turbine-drive and rotor disk) was dynamically balanced as a single unit before experimental runs in the transonic region were attempted.

B. TURBINE-DRIVEN FUEL PUMP

The rotor was driven by the turbine of a Hamilton-Standard fuel pump, Model TPC-13, mounted and enclosed in the spin chamber. An 8000 cu. ft., 300 psi air supply was used to operate the turbine. However, only 10-20 psi air was needed to operate the turbine at speeds in excess of 25,000 rpm. [Ref. 11]. Turbine bearing lubrication was provided by a Brown and Sharpe oil pump providing 40 psi gauge pressure, with the oil returned to the reservoir via a separate scavenge pump. Scavenged oil was cooled via a heat exchanger before flowing into the reservoir. The lubrication system is shown in Figure 4. The temperature of the oil exiting from the turbine, an indication of the turbine bearing operating temperature, was monitored throughout the run cycle. Details of the fuel pump are given in Reference 11.

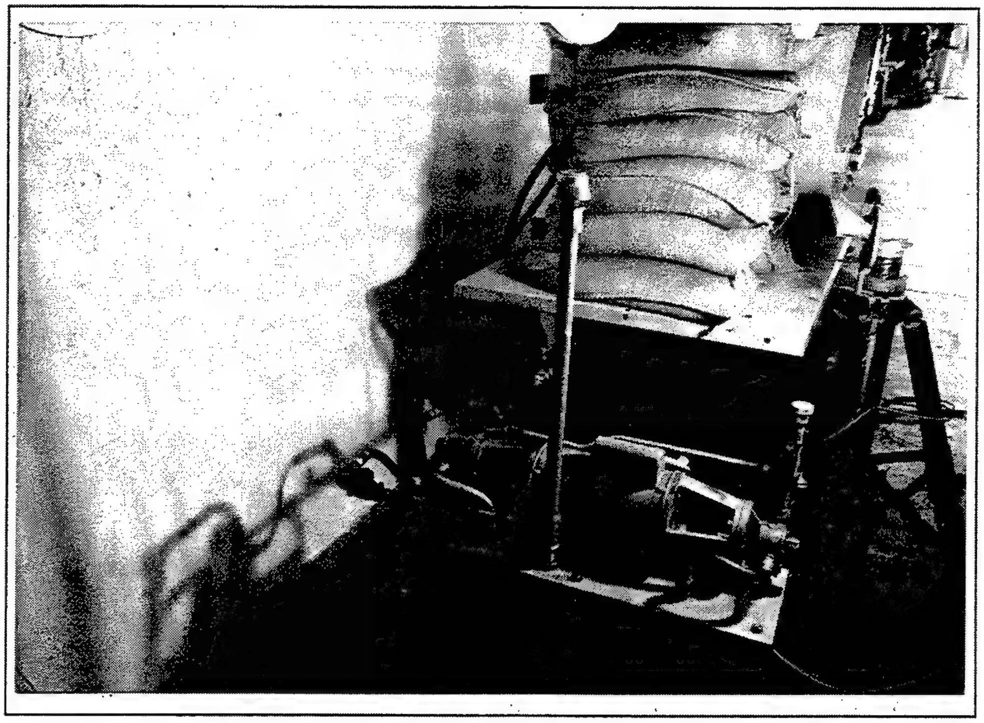


Figure 4. Lubrication System

C. IMAGE CAPTURE AND PROCESSING ASSEMBLY

1. Rotor Illumination System

The rotor was illuminated through an open hole in the center of the cover plate of the spin chamber using an Oriel 1000-Watt quartz tungsten-halogen lamp, Model 66187 with a F/0.7 condensing lens assembly [Ref. 13]. The lamp was fitted with an Oriel blue-gel and interference filters (#66228 and #575, respectively) which provided illumination with the wavelength centered at 380nm. The lamp was supplied with variable AC voltage via an Oriel lamp controller, Model 6405-M. The control voltage was adjusted to 118% of line voltage to ensure ample illumination uniformly across the disk surface. Control voltage to the lamp was turned off between image capture periods to preserve the

luminescent characteristics of the PSP. The lamp and camera set up are shown in Figure 5. Camera access was through a separate hole in the cover plate.

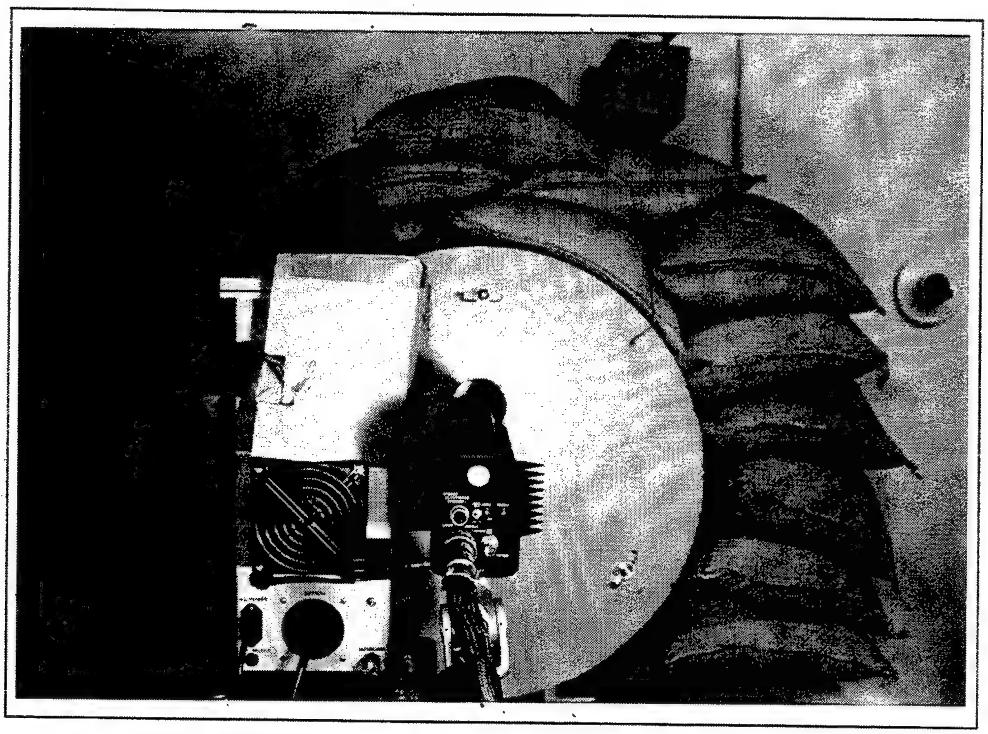


Figure 5. Camera, Lamp, and Rotor Disk Housing

2. Camera System

Rotor disk images were acquired using a Xybion ISG-350, externally triggered and gated CCD camera. A remote Xybion Camera Control Unit (CCU) was used to control the camera's triggering and gating functions through a 23-pin multipurpose connector [Ref. 14]. The camera was fitted with a 75mm, f1.4 Cosmicar™ television lens and an Oriel interference filter #53590 to limit the camera's spectral response to the desired 650 nm wavelength. The PSP illumination system and camera set up on the spin chamber are shown in Figure 5. A timing diagram for the camera control

is shown in Figure 6. A 5-volt external trigger pulse (D) was used to trigger camera exposure while the range gate function of the CCU determined the length of exposure. The exposure period was varied, depending on the rotor disk RPM, and was set so that the captured image was focused. Multiple exposures were obtained to form a single image through the use of an externally applied image inhibit transistor-transistor logic (TTL) low signal. The image-inhibit TTL high-low transition allowed the integrated exposures to be captured as a single image. Similar to the procedure for setting exposure duration times, image-inhibit signal periods were based on the rotor disk RPM. Camera and intensifier gain were controlled manually from the CCU.

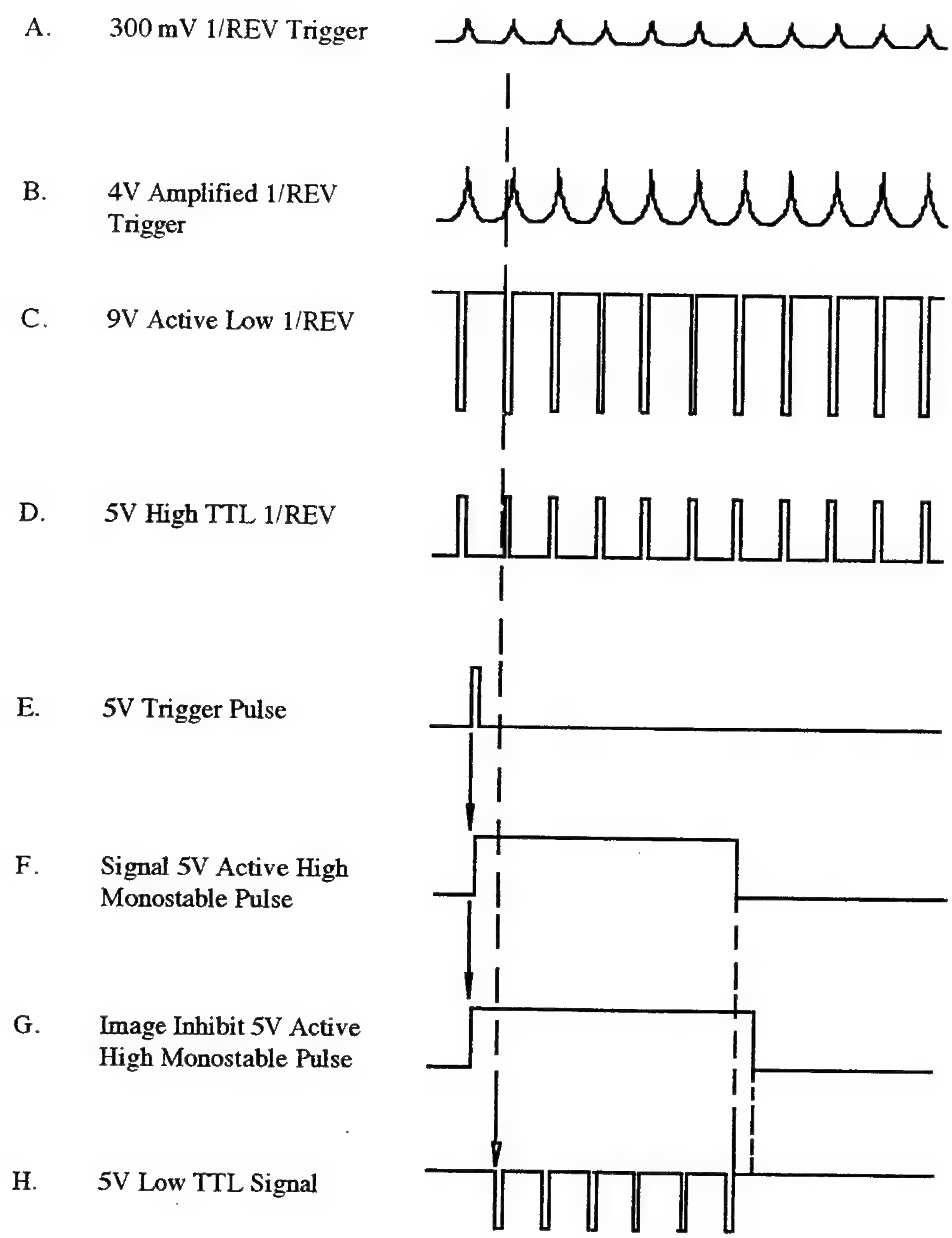


Figure 6. Image Capture Timing Sequence

Source: Quinn, K. J., "Pressure-Sensitive Paint Measurement Technique Development for Turbomachinery Application," M.S. Thesis, Naval Postgraduate School, Monterey, California.

3. Once-Per-Revolution Trigger

The image trigger was supplied by a light-emitting diode (LED) illuminating a photodiode. The photodiode when illuminated (once-per-revolution) triggered a +50 millivolt pulse that was amplified and converter to 5 volt TTL active-low format required by the imaging circuitry [Ref. 2].

4. Imaging System

A high-low transition of the 5 volt TTL signal was used to expose the camera intensifier and image the rotor disk PSP area. Multiple exposures were integrated only during periods when the image-inhibit function was activated (+5 VDC) and were captured to a single image when the function transitioned from high to low. Activation and duration of the image-inhibit function was controlled by a Wavetek function generator and separate resistor-capacitor (RC) time constants respectively [Ref. 2]. Additionally, the duration of the camera exposure was set using the CCU. An exposure time of 500 nanoseconds was required to adequately focus and freeze the moving image. A trial-and-error procedure was used to adjust the intensity of the captured image at different wheel speeds. As the exposure time required for focusing was decreased, longer integration periods were required to be set using the image-inhibit function. Images were captured using an EPIX 4MEG Video Model 12 integrated circuit board and EPIX 4MIP V3.2 software installed in a 120MHz Pentium personal computer [Ref. 15]. Software scripts were developed so that the image acquisition was completed autonomously. Ten

images were captured each for wind-off, wind-on, and dark-current image. These images were then processed by taking the ratio between them to develop a single image.

IV. EXPERIMENTAL PROGRAM

A. PROCEDURES

The PSP test methodology was similar to that discussed in references 1 and 10. In order to produce significant static pressure variations on the plate surface, tip Mach numbers of the order of 0.9 (1015.2 ft/sec) and above were required. The rim area surrounding the shock generator was painted with an initial coating of glossy white interior/exterior Krylon paint. PSP was air-bushed onto the surface after the Krylon paint had dried. Subsequently, experimental runs with PSP only applied to the rotor disk were also attempted. Figure 7 shows the painted areas of the rotor disk. Both paint applications were done with the rotor installed on the turbine. This procedure reduced the

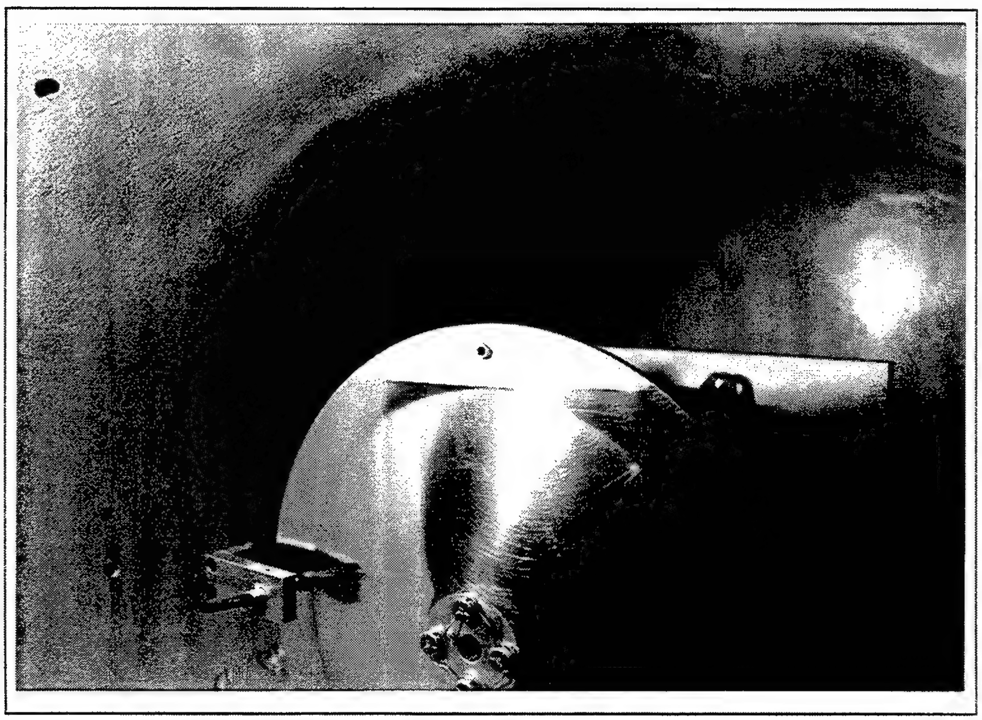


Figure 7. Rotor Disk Paint Area

PSP degradation that results from exposure to room light. Floor markings for the camera set up were used to ensure repeatability. Minor adjustments of the camera position were used to center the shock generator in the image. The camera focal adjustments were used to optimize the image clarity [Ref. 14].

Camera gate durations were set to optimize the image focus and then the image-inhibit signal time was adjusted to maintain adequate image intensity. Since rotor wheel speed was maintained at +/- 1 Hz, gate duration time was calculated to limit rotor travel to approximately .007 inches in order to prevent blurred images [Ref. 2]. Table 1 shows the gate duration times used for the reported run conditions.

RPM	Frequency (Hz)	Rotor Speed (ft/sec)	Mach #	Image Inhibit Signal (secs)	Number of Exposures	Gate Duration (nsecs)
20,000	333	1047.20	0.93	8.0	2663	560
23,400	390	1225.22	1.08	12.8	4992	470

Table 1. Gate Duration Times for Rotor Travel of .007 inches

Since gate duration times could not be set exactly, a trial-and-error procedure was used to vary the image-inhibit and gate-duration times to optimize image intensity and focus. Table 1 shows the length of the image-inhibit signal used with two different gate durations, and the corresponding number of integrated exposures necessary to produce a usable image.

An image acquisition script was written with a "time delay" included to allow the wheel to be operated remotely after execution was triggered at the keyboard. The scripts developed for image acquisition are given in Appendix A. After wind-on images were captured, averaged, and saved as a TIFF file, the process was repeated for wind-off images. Wind-off images were captured after wind-on images were obtained in an attempt to ensure that the surface temperature of the rotor was as near as possible to those during the wind-on tests. To remove the thermal noise generated by the camera, dark current images were obtained and subtracted from both the wind-on and wind-off images. The two images were first aligned and then the ratio (wind-off/wind-on) was computed and multiplied by a scaling factor to produce a final image corresponding to the left hand side of the Stern-Volmer relation (I_o/I). This final 0-255 grey-scale image represented the inverse pressure ratio of wind-on to wind-off in accordance with equation (1). A histogram showing frequency of individual pixel intensity values was inspected in order to select the range of minimum intensity to maximum intensity for further processing. The pseudo-coloring technique reported by Seivweight [Ref. 1] was applied to obtain the final image.

Appendix B details the methodology developed for the PSP set up and procedure.

B. PROGRAM OF TESTS

In previous studies, rotational speeds were limited by available power [Ref. 2] or by rotational stresses and lubrication [Ref. 3]. In the present study, the construction of a new high-speed rotor was intended to extend the test capability to 30,000 RPM.

After mounting the rotor to the drive turbine, which was fitted to the shaft with dowels, the unit was dynamically balanced, installed in the spin chamber, and operated at progressively increased speeds. Using the lubrication system described by Quinn [Ref. 3], rotational speeds were found to be limited to about 20,000 RPM. When the hydraulic pump was replaced with a combination lubrication-supply and scavenge-pump system, oil temperatures again reached 175° F after minutes of operation. A shell-and-tube (water supplied) heat-exchanger was installed in the oil return line and was found to keep oil temperatures steady below 135° F.

In order to extend testing above 20,000 RPM, the acquisition software was modified so that the operator could move to a protected control room and remotely operate the drive turbine. A series of tests was then conducted using PSP at increasing rotor speeds. Results for 23,400 RPM are described and discussed in the following section. Higher speeds were not attempted when it was found that the present paint could not withstand supersonic tip speeds, and that the RPM indication was lost.

V. RESULTS AND DISCUSSION

The rotor disk configuration for each in a series of four tests is shown in Table 2. Complete images were acquired successfully in Run 1. In Run 2, at rotor tip speeds above Mach 1.0, paint stripping occurred in the local area surrounding the shock generator. In an attempt to prevent the paint from coming off, in Run 3 PSP was applied to the rotor disk without the Krylon undercoat. While the test showed that sufficient intensity could be accumulated without using the Krylon, the PSP again came off around the shock generator. Increasing blade surface roughness using a bead-blasting technique before applying PSP only, was attempted in Run 4. In Run 4, as well in all experimental runs over Mach 1.0, a loss of paint occurred in the local area surrounding the shock generator.

RUN	RPM	PAINT	ROTOR SURFACE
1	20,000	Krylon + PSP	Smooth
2	23,400	Krylon + PSP	Smooth
3	23,400	PSP	Smooth
4	23,400	PSP	Rough

Table 2. Rotor Disk Configuration

Pseudo-colored images of the intensity ratio (I_0/I) for Runs 1 through 3 are shown in Figures 8 - 10, respectively. A grey-scale wind-off image of Run 2 is shown in Figure 11. Figure 12 shows a grey-scale wind-off image of Run 4.

The pseudo-colored image of the intensity ratio (I_0/I) for Run 1, shown in Figure 8, clearly shows a non-uniform intensity distribution varying from red (lowest intensity ratio/lowest pressure) to blue (highest intensity ratio/highest pressure). A histogram showing the frequency (number of pixels) vs. pixel value (intensity) of the image ratio (I_0/I) multiplied by a factor of 50 is shown in Figure 13. Pixel value plots for a horizontal line 10 pixels above and below the set-screw are shown in Figures 14 and 15, respectively. In a two-dimensional uniform flow, at a speed of 1047 ft/sec (Mach number = 0.9), a shock would occur just behind the maximum diameter of the shock generator as the airflow velocity is first increased to supersonic then decreased to subsonic Mach number conditions. The resultant intensity distribution in Figure 8, if interpreted to represent the surface pressure distribution is not consistent with what would be expected for transonic flow over the shock generator. The plotted intensity ratio distribution should show a low-high variation across a shock. No such transition is evident. Varner [Ref. 2] discusses the viscous pumping effect of a rotating disk in which air is sucked along the centerline axis and pumped radially outward along the surface of the disk. Qualitatively, with respect to Figure 8, stagnation from the pumping effect would not be consistent with the red-yellow areas (indicating lower pressure) along the inner portion of the shock generator. However, since a portion of the set-screw threads were slightly

exposed above the disk surface, stagnation areas could occur, which would be consistent with the dark blue areas along the leading semi-circle of the set-screw.

An alternate explanation for the intensity ratio distribution radially along the disk surface, is that it results from the increased stagnation temperature as wheel velocity increases with radius. A strong temperature gradient effect was reported by Quinn (Ref. 3), however, the present disk had a much higher thermal capacity than the 0.25 inch plate used by Quinn, and more nearly uniform temperatures would be expected.

Results in Figure 13 indicated that the significant pixel value range in Run 1 extended from approximately 50-150 across the disk surface. Results in Figures 14 and 15 show a slightly negative slope of surface intensity ratio from leading to trailing edge of the image, implying a decreasing pressure and/or temperature.

The psuedo-colored image of the intensity ratio for Run 2, shown in Figure 9, illustrates the paint stripping effect that occurred at higher rotation speeds. Where the paint came off is consistent with the occurrence of a detached , and possibly unsteady, shock. A shock positioned in front of the shock generator would interact with the boundary layer on the disk surface. The gray-scale image from Run 2 in Figure 11, shows the exact location where the paint came off. Intensity ratio distributions for Run 2 showed a high-to-low intensity gradient horizontally across the set-screw and a nearly uniform intensity distribution below and behind the shock generator. This intensity ratio distribution would be inconsistent with respect to the pressure distribution from a bow shock located in front of the set-screw. Possible temperature effects similar to those in Run 1 can be seen in front of the area where the paint was stripped. A histogram showing

the frequency (number of pixels) vs. pixel value (intensity) of the image ratio (I_0/I) is shown in Figure 16.

The pseudo-colored image of the intensity ratio (I_0/I) for Run 3, for which PSP was applied without Krylon, is shown in Figure 10. The intensity ratio distribution is seen to be similar to that of Run 2, with the exception that the paint was stripped above the set-screw. The paint stripping above the set-screw was not repeated in two similar experimental runs. Runs at similar conditions to Run 3 produced paint stripping only in front of the set-screw, similar to Run 2. A histogram showing the frequency (number of pixels) vs. pixel value (intensity) of the image ratio (I_0/I) for Run 3 is shown in Figure 17.

Finally, the result of the attempt made to keep the paint from stripping by roughing the surface using the bead-blasting technique, is shown in Figure 12. Paint stripping occurred in the local area in front of the set-screw similar to Runs 2 and 3.

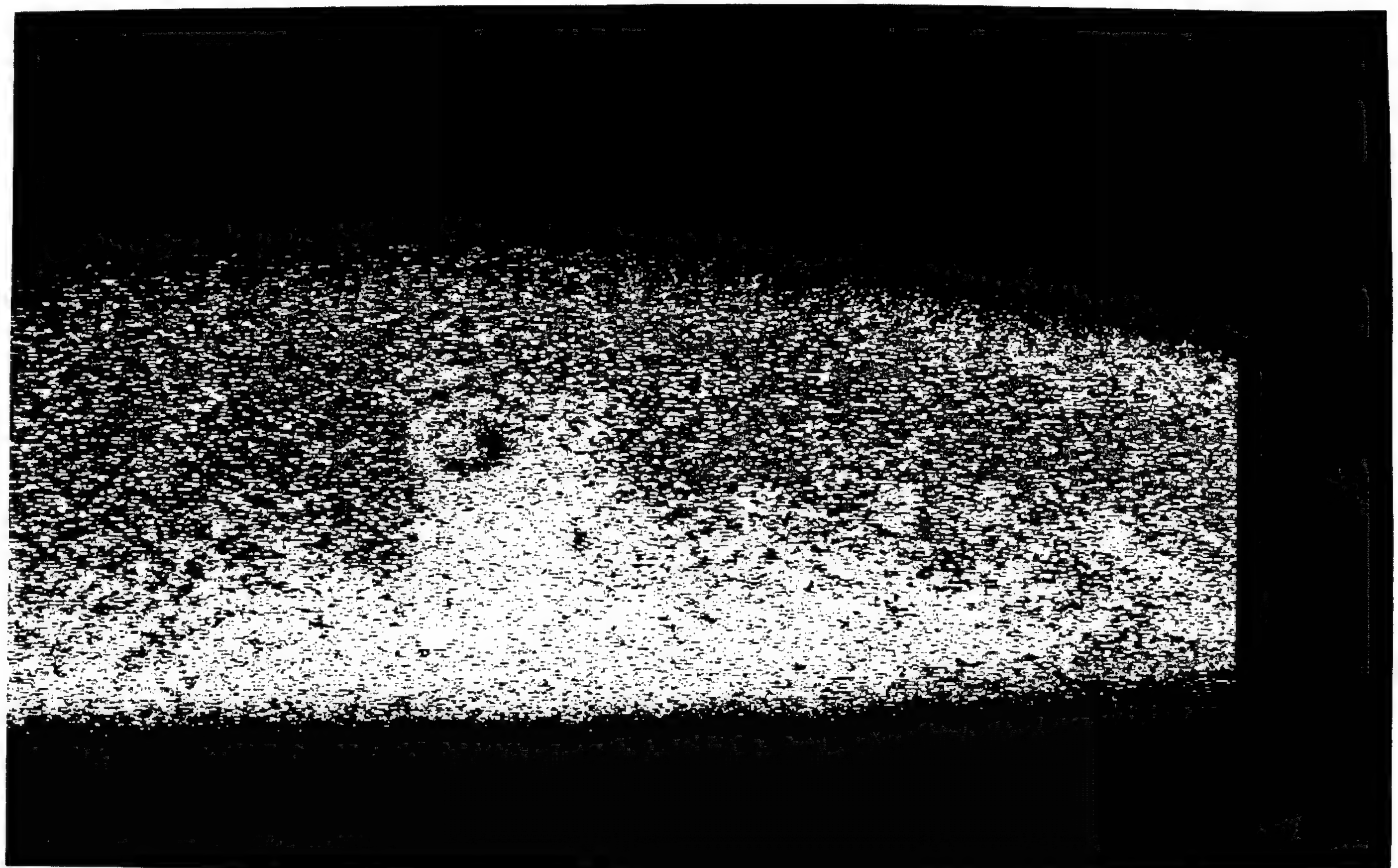


Figure 8. Image Intensity Ratio (I_0/I) for 20,000 RPM

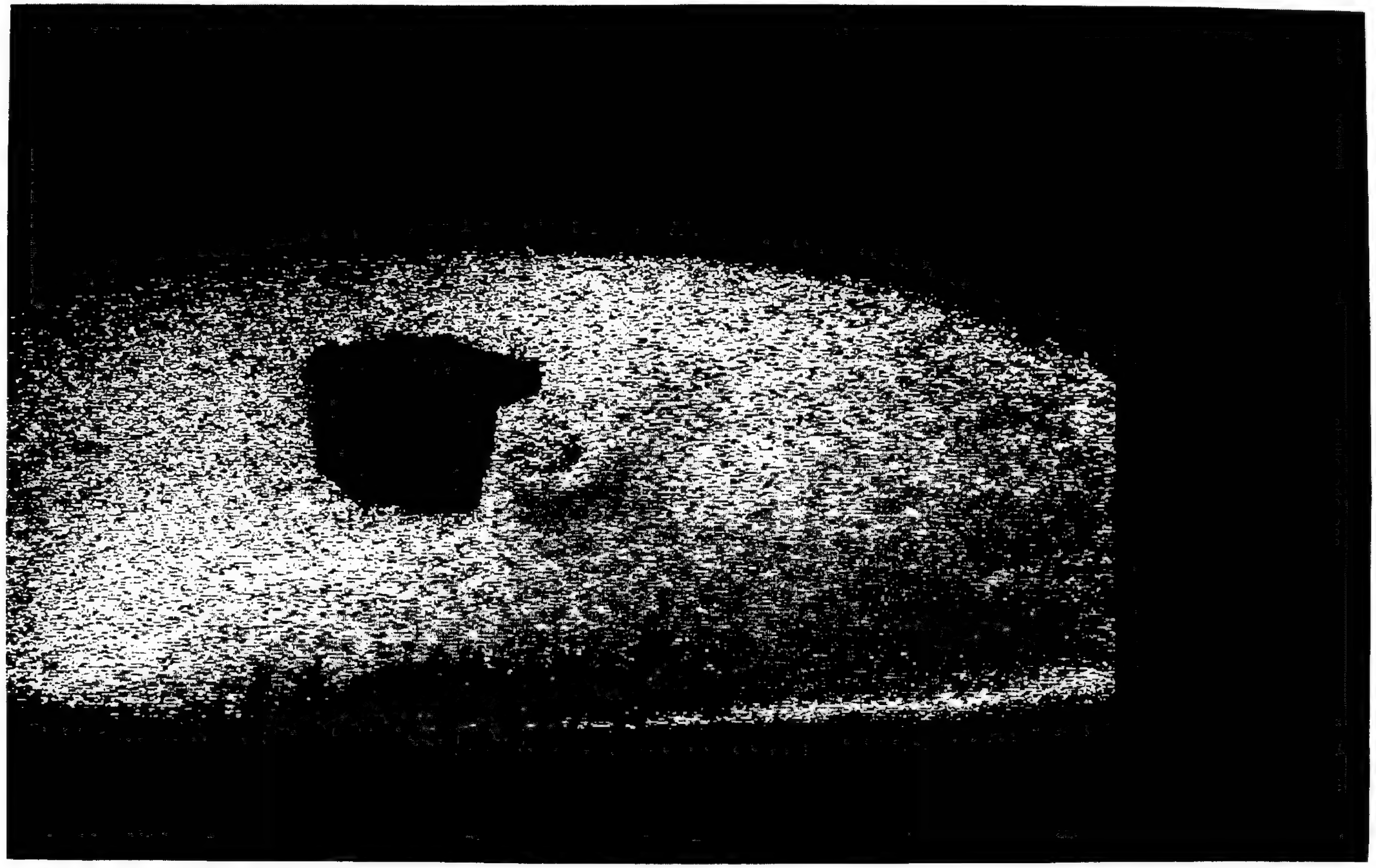


Figure 9. Image Intensity Ratio (I_0/I) for 23,400 RPM - Run 2

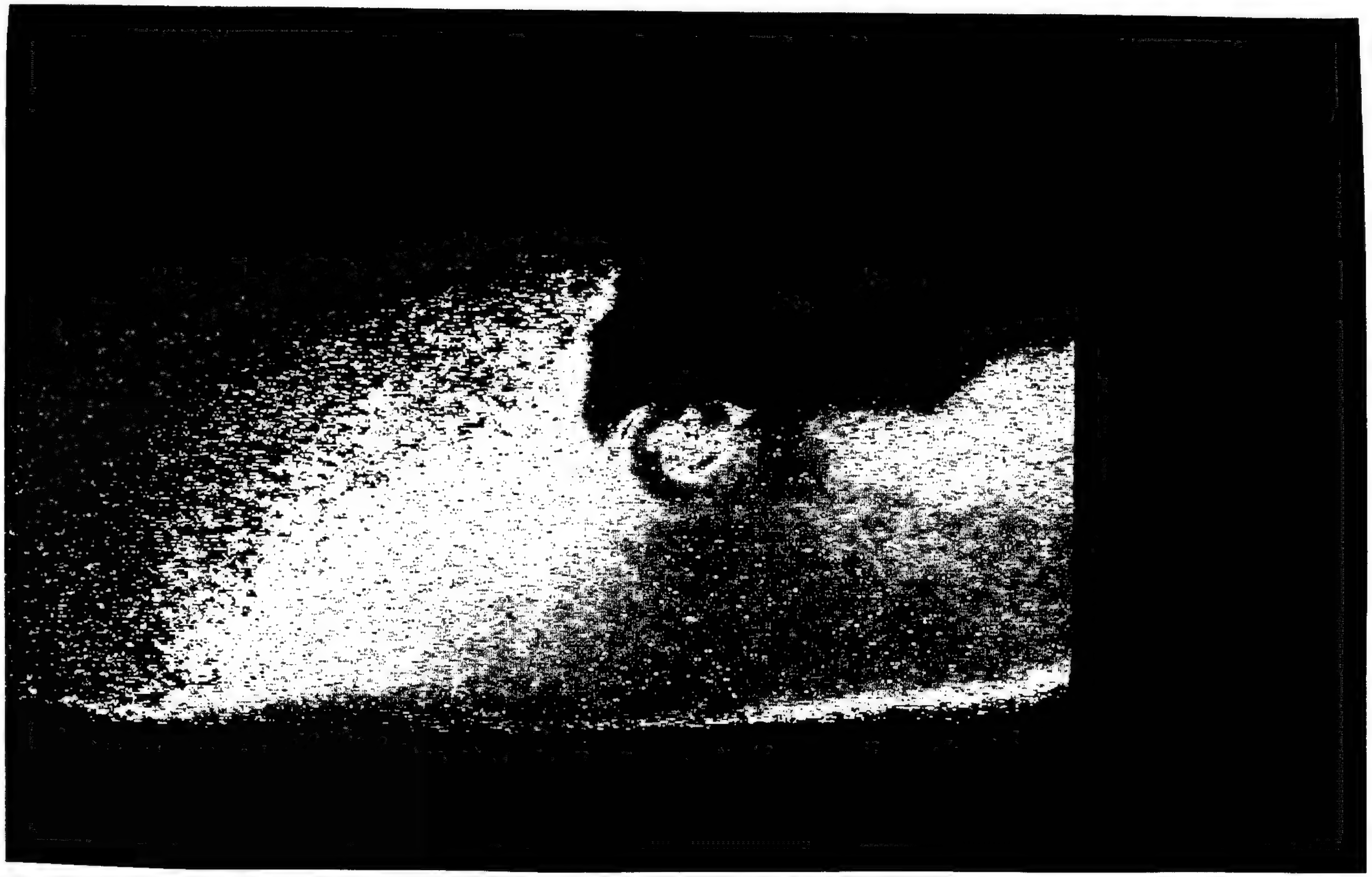


Figure 10. Image Intensity Ratio (I_0/I) for 23,400 RPM - Run 3

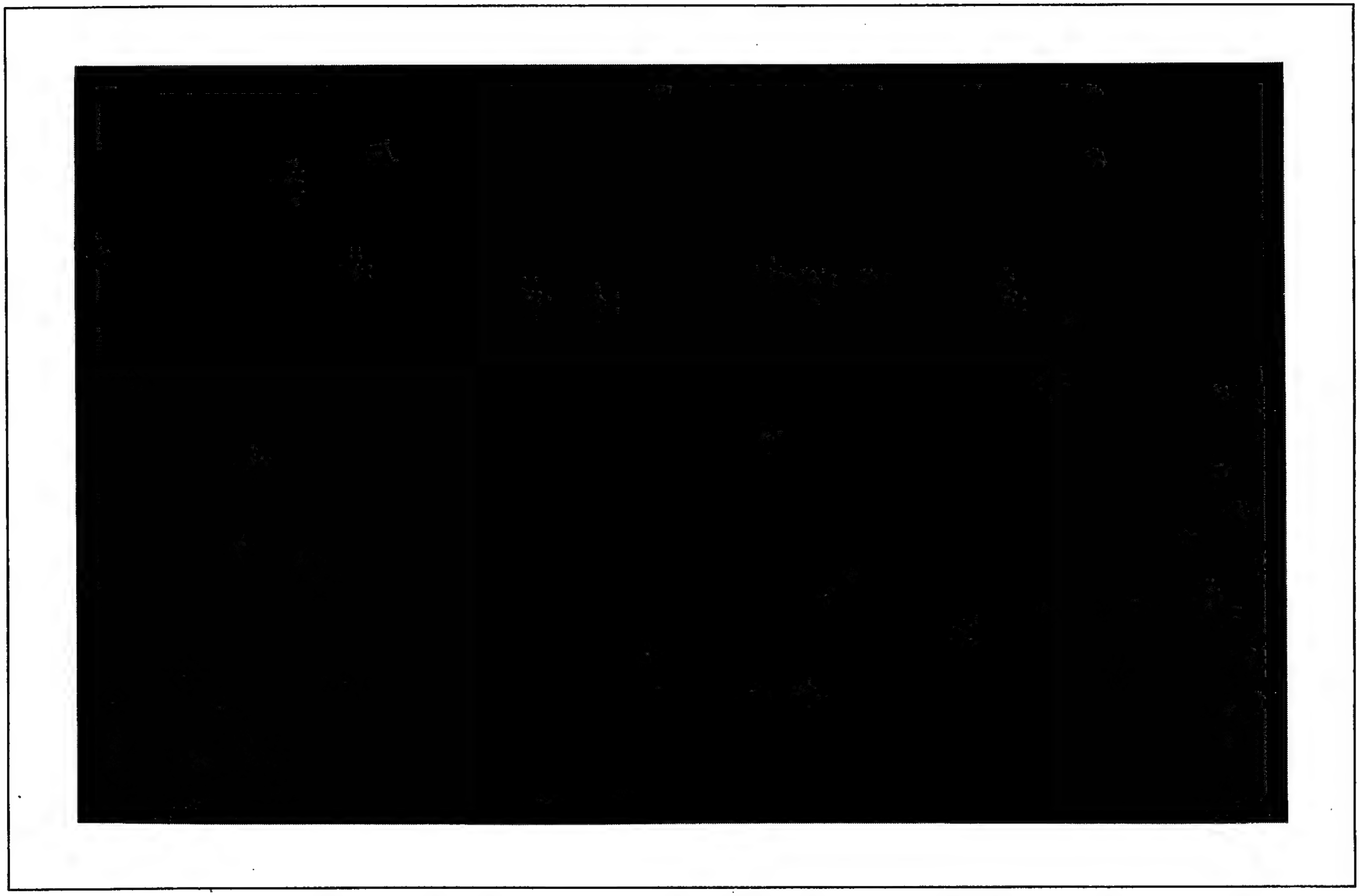


Figure 11. 256 Grey-Scale Intensity Ratio (I_0/I) for 23,400 RPM - Run 2

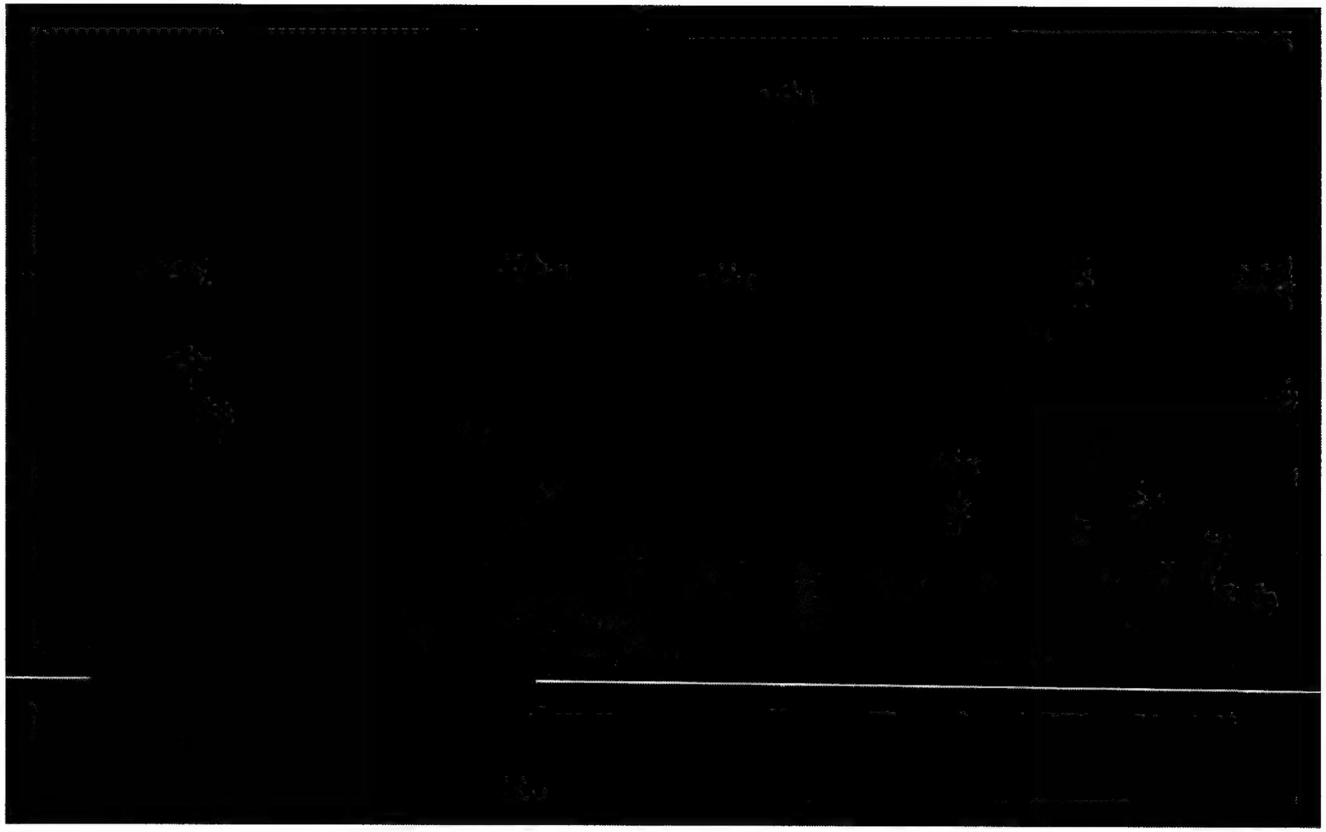


Figure 12. 256 Grey Scale Intensity Ratio (I_0/I) for 23,400 RPM - Run 4

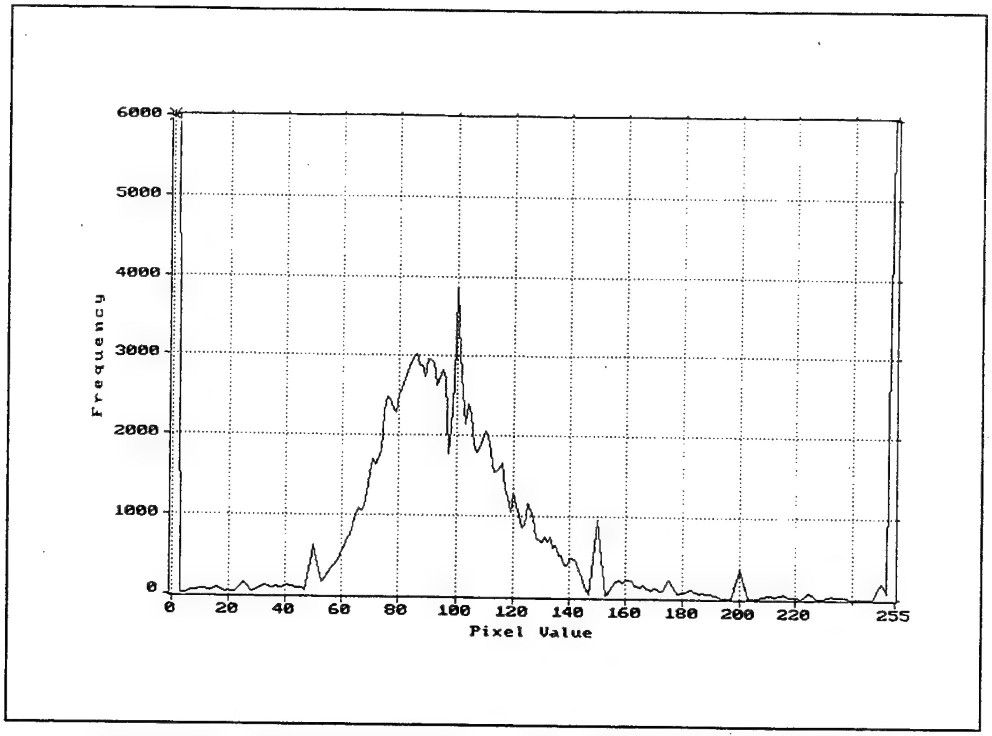


Figure 13. Pixel Frequency vs Intensity Ratio (20,000 RPM)

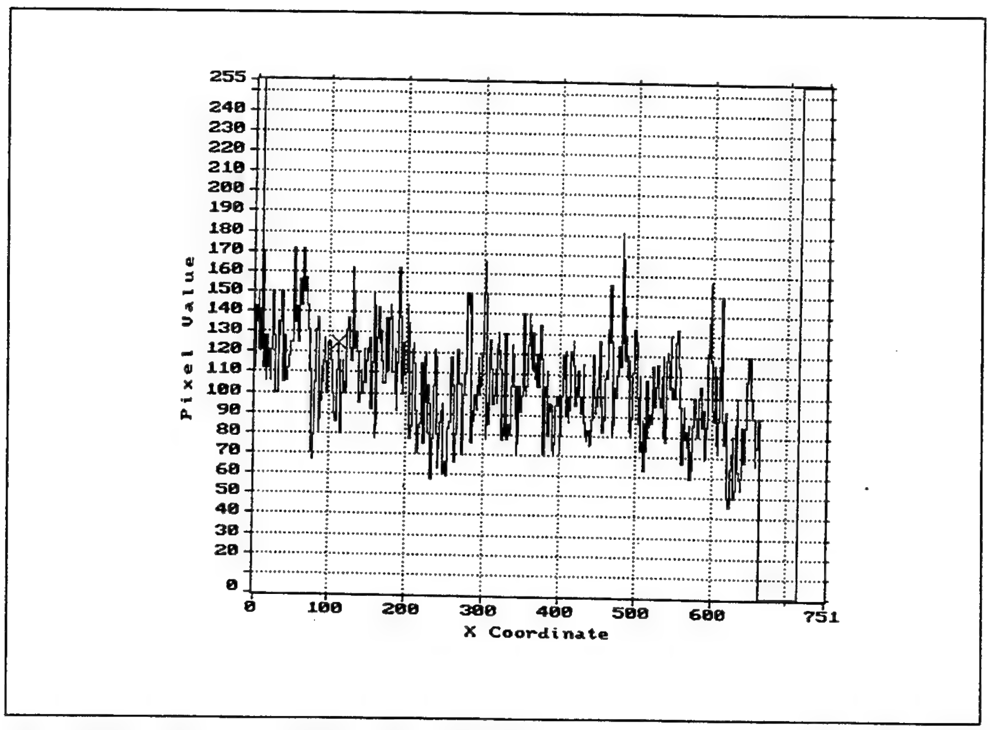


Figure 14. Pixel Value vs. Single Line of Pixels Above Set-Screw (20,000 RPM)

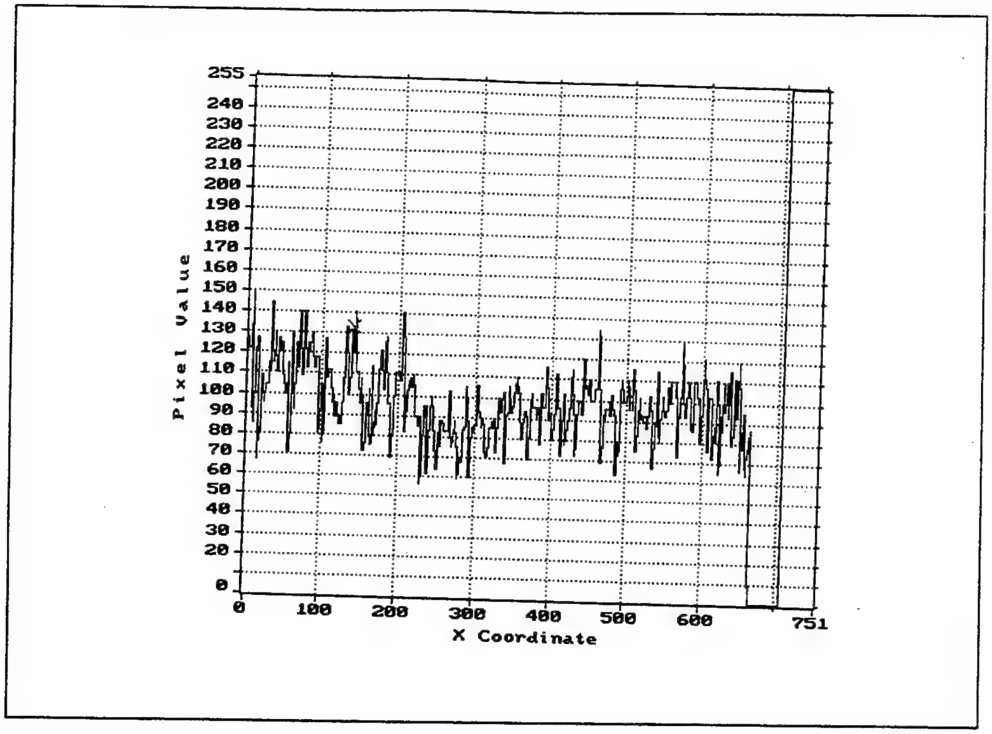


Figure 15. Pixel Value vs. Single Line of Pixels Below Set-Screw (20,000 RPM)

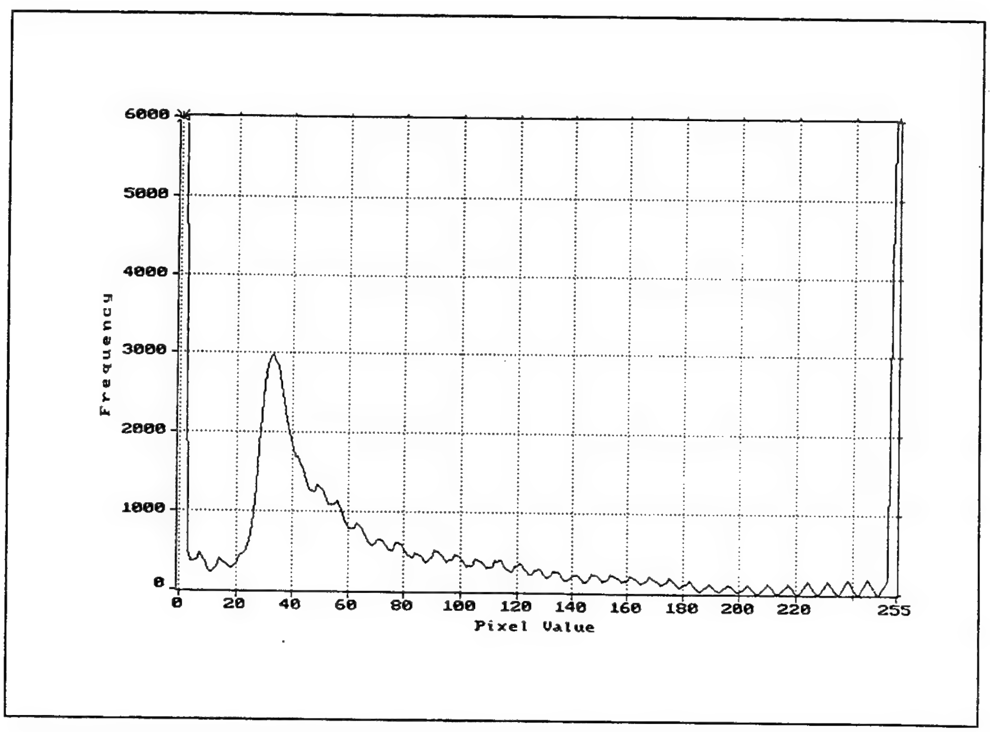


Figure 16. Pixel Frequency vs. Intensity Ratio (23,400 RPM/Run 2)

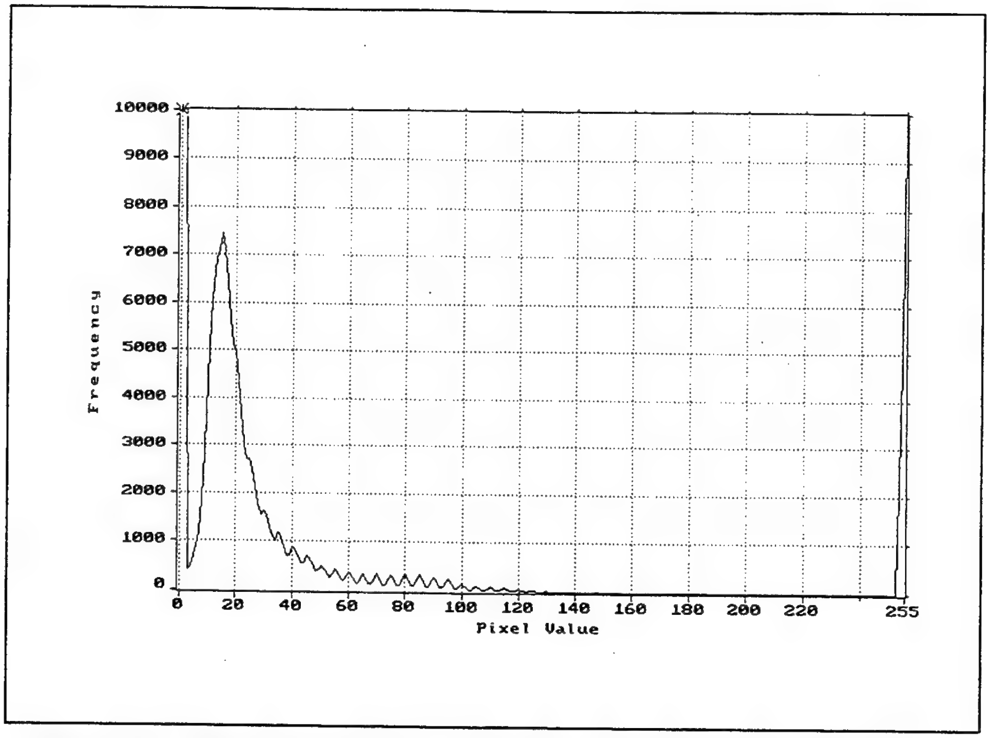


Figure 17. Pixel Frequency vs. Intensity Ratio (23,400 RPM/Run 3)

VI. CONCLUSIONS AND RECOMMENDATIONS

A high-speed rotor test facility using pressure-sensitive paint to obtain surface-pressure distributions has been developed and operated successfully. Additionally, focused PSP image intensity-ratio maps were produced at subsonic and supersonic speeds. At supersonic wheel speeds, paint stripping around the leading edge of the shock generator occurred. A more adhesive paint was required for operation at supersonic speeds. The facility itself was shown to be a suitable test bed for developing quantitative PSP measurements before application on a transonic compressor rig.

To continue the development of the PSP measurement technique for supersonic speeds and transonic rotors, the following are recommended:

1. Install more responsive LED photodiodes to provide RPM counter readings at higher rotation speeds. Alternatively, enlarge the 1/rev hole to increase the amount of light passed to the detector.
2. Investigate paint and application techniques that provide good PSP adherence at supersonic rim wheel speeds.
3. Investigate methods for separating pressure and temperature effects quantitatively.
4. In 2 and 3, develop techniques that are suitable for use on the transonic - compressor rig, where surfaces are curved, access is more limited, and the rotor can not be removed readily between tests

APPENDIX A: PSP SCRIPTS

Executable 4MIP TOOL scripts developed by Quinn [Ref. 2] were modified to provide "hands-off" and remote image capture. An executable pause was incorporated into the AVG.TEST script to provide time to start up the drive turbine and for the RPM to stabilize before image acquisition. Additionally, the command "Trigger: External Input" was activated during the image acquisition period to synchronise CCU and EPIX software frame-grabber board data transfer and receive rates. Synchronisation was reverted back to the RS170 14.3MHz rate at image acquisition completion. Script AVG.TEST provided the complete image acquisition executable file; CHECKERT.MPX provided a quick feedback showing the 10 images captured; and PSP_AVGT.MPX averaged the 10 images to produce a single captured image.

AVG.TEST

```
 {!}pause 1
 <QuitMenu
 >SpecialOperations&Modes
 >TriggerImageCapture
 >6)WaitNfields.N: 2
 <QuitMenu
 <QuitMenu
 >MotionSequenceCapture/Display
 >TriggerOptions
 Trigger:ExternalInput[**]
 ^DelayedbyNfields.N: 1
 <QuitMenu
 <QuitMemu
 >VideoFormats
 >CustomInterfaceModes
 !ExternalPixelClock
 <QuitMenu
 <QuitMenu
    {!}KEY 0x5900 SF6
    ^Screen1Height     10
    ^Screen2Height     9
    ^Screen3Height     9
    !SetSplitScreen
  <QuitMenu
>VideoDigitize/Display
  !CurrentImageBuffer1
  {!}KEY 0x4000 F6
>SpecialOperations&Modes
  >TriggeredImageCapture
   !ExecuteTriggeredCapture:
   {!}KEY 0x4000 F6
{!}KEY 0x4000 F6
 !CurrentImageBuffer2
 {!}KEY 0x4000 F6
   !ExecuteTriggeredCapture:
   {!}KEY 0x4000 F6
{!}KEY 0x4000 F6
 !CurrentImageBuffer3
 {!}KEY 0x4000 F6
```

```
    !ExecuteTriggeredCapture:
    {!}KEY 0x4000 F6
 {!}KEY 0x4000 F6
  !CurrentImageBuffer4
   {!}KEY 0x4000 F6
    !ExecuteTriggeredCapture:
    {!}KEY 0x4000 F6
 {!}KEY 0x4000 F6
  !CurrentImageBuffer5
   {!}KEY 0x4000 F6
    !ExecuteTriggeredCapture:
    {!}KEY 0x4000 F6
 {!}KEY 0x4000 F6
  !CurrentImageBuffer6
   {!}KEY 0x4000 F6
    !ExecuteTriggeredCapture:
    {!}KEY 0x4000 F6
 {!}KEY 0x4000 F6
  !CurrentImageBuffer7
   {!}KEY 0x4000 F6
    !ExecuteTriggeredCapture:
    {!}KEY 0x4000 F6
 {!}KEY 0x4000 F6
  !CurrentImageBuffer8
   {!}KEY 0x4000 F6
    !ExecuteTriggeredCapture:
    {!}KEY 0x4000 F6
 {!}KEY 0x4000 F6
  !CurrentImageBuffer9
   {!}KEY 0x4000 F6
    !ExecuteTriggeredCapture:
    {!}KEY 0x4000 F6
 {!}KEY 0x4000 F6
  !CurrentImageBuffer10
   {!}KEY 0x4000 F6
    !ExecuteTriggeredCapture:
 <QuitMenu
  {!}KEY 0x4000 F6
>MIPXScripts
  !ExecuteMIPXScriptFile.Name:  scripts/checkert.mpx
  !ExecuteMIPXScriptFile.Name:  scripts/checkert.mpx
  !ExecuteMIPXScriptFile.Name:  scripts/psp_avgt.mpx
  <QuitMenu
  <QuitMenu
```

```
    {!}KEY 0x5900 SF6
    ^Screen1Height    30
    ^Screen2Height     0
    ^Screen3Height     0
    !SetSplitScreen
  <QuitMenu
>VideoFormats
!SetFormat:RS-170iff14.3MHzClock
<QuitMenu
<QuitMenu
```

PSPAVGT.MPX

```
<QuitMenu
 >VideoDigitize/Display
 !CurrentImageBuffer 1
 <QuitMenu
>ImageProcessing
 >ImageSequenceOperations
   ~SequenceStartingBuffer 1
   ~SequenceEndingBuffer     10
   !AverageImageSequence
     !ImageAreaofInterest:FullImage
   <QuitMenu
  <QuitMenu
>MIPXScripts
```

CHECKERT.MPX

```
<QuitMenu
>VideoDigitize/Display
  !CurrentImageBuffer1
  !CurrentImageBuffer2
  !CurrentImageBuffer3
  !CurrentImageBuffer4
  !CurrentImageBuffer5
  !CurrentImageBuffer6
  !CurrentImageBuffer7
  !CurrentImageBuffer8
  !CurrentImageBuffer9
  !CurrentImageBuffer10
 <QuitMenu
>MIPXScripts
```

APPENDIX B. PSP SETUP AND PROCEDURE

The following describes the current procedure for PSP measurements over a rotor disk using the PSP test bed facility. The procedures assume all of the test bed elements of the test bed are available.

1. Compressed Air Setup Procedures

- Check that all access valves are closed.

- Check air pressure gauge (>50 psi is required for sustained runs above 20,000 RPM).

- Switch MOV - ON

- Open line to charge manifold

- Charge lines by opening access valves (2-3 turns).

- Apply power to oil cooling pump; adjust setting for oil pressure of 38 psi and control valve set ½ turn.

- Open cooling water valve 1 turn.

- Ensure remote activation set-up

2. Rotor Disk Attachment To Turbine Driven Fuel Pump.

- Use 3/32 allen wrench to slide LED and photodiode back into attaching plate before attaching rotor disk; this clears area to avoid contact with rotor disk preventing dents, scratches, etc.

- Slide rotor disk onto dowels on turbine drive flange while avoiding contact with LED mounting bracket. Dowels are different diameters to prevent improper attachment of rotor disk.

- Press wheel fully onto turbine drive flange and insert attachment bolts (all bolts are similar size) and tighten using 7/16" wrench. Safety wire all four bolts with .032" diameter wire.

3. Krylon Paint Application

- Align rotor disk with shock generator at 12 o'clock position; 3/32" transparent hole will be aligned with LED and photodiode.

- Clean rotor disk with acetone to remove greasy film and or contamination before applying paint. Let dry for 1-2 minutes.

- Attach cardboard mask for paint application; LED and photodiode should be completely covered prior to painting.

- Apply a thin layer (1-2 coats) of glossy Interior/Exterior Krylon paint (#1501); Avoid paint drips and/or runs along rotor disk. Let dry for approximately 30-45 minutes or until dry.

4. PSP Application

- Clean airbrush and PSP paint container thoroughly with acetone and let dry; this avoids contamination of PSP before application.

- Connect airbrush hose to N_2 bottle and set pressure to approximately 40 psi; check for proper operation.

- Half fill PSP container and attach to airbrush

- LIMIT PSP EXPOSURE TO LIGHT AS MUCH AS POSSIBLE TO AVOID DEGRADATION OF THE PAINT.

- Spray PSP 8-10 inches from rotor disk surface in a sweeping motion; again avoid any drips, runs or excessive concentration areas of paint. Apply paint until a smooth, even finish is evident (approximately 1- 2 minutes of airbrush time).

- Turn lights off in the room and let dry for approximately 10 minutes.

- Remove cardboard mask and check area for smooth paint application: (Excessive paint application will cause weight imbalances on the rotor disk).

- Adjust LED and photodiode to as close as 1/16 inch (trial and error procedure is required to obtain proper RPM pick-up 1/16 inch is too large for speeds of 30,000 RPM).

- Hand spin wheel to ensure proper clearance and that the wheel rotates unhindered.

- Attach spin chamber cover plate and lock down with washer and bolts.

- Slide Oriel light source into position (markings on floor provide most effective lamp positioning for uniform and sufficient illumination over rotor disk).

- Position camera using markings on the floor.

- Turn on LED and rotate disk until 3/32" hole is located in the center.

5. Image Focusing

- Disconnect image inhibit BNC connector on back of CCU (this step is required since an erroneously high setting of image inhibit signal is possible in the non-powered state).

- Disconnect BNC "Vin" from CCU to CP and connect to Video In Line A on back of Sony the monitor.

- Set trigger source on CCU to "VD", set camera gain to "max", set intensity to "max", and set range to either 100μs or higher to see real-time image (to avoid intensifier damage start range at a lower setting and adjust higher later until image is viewed)

- Increase line voltage to Oriel lamp to 118%

- Only "A/RGB" position on front of Sony monitor should be illuminated to view real-time image.

- Focus image using camera focus and move camera position to center image on monitor; focal length of camera can be changed by adjusting position of the entire lens assembly (refer to Xybion reference manual before adjusting).

- Once image is centered and properly focused, turn off Oriel lamp and reinstall image inhibit BNC connector (Wavetek pulse function generator that supplies the image inhibit pulse should be off before connecting image inhibit connector to CCU)

- Connect "Vin" input to computer and select "L/RGB" on the Sony monitor front panel (both "A/RGB" and "L/RGB" should be illuminated).

- Set trigger source on CCU to "EXT" and select proper range gate (range gate will vary depending camera exposures times required)

6. Software Set-up

The main EPIX program script is called AVG.MPX and incorporates LOOK and AVERAGE scripts. AVG.MPX, which incorporates a execution delay time, is used to

capture images for wind-on conditions; AVGF.MPX is developed for wind-off and "dark current" image capture. Software script can only be used for EPIX 4MIP but can be modified for use with 5MIP version.

- Open EPIX 4MIP program and select the "MIPX Scripts" option from the main menu; enter file name "c:\4mip\scripts\avg.mpx" in the execute MIPX script file prompt. Use a stop-watch to monitor elapsed time.

- Set Oriel lamp control voltage to 118% to illuminate rotor disk and turn off lights when exiting room and close all access doors.

7. Rotation of Rotor Disk

- From remote activation area slowly turn control valve CW for air supply to turbine. CAUTION: Avoid over-speeding rotor disk with excess air supply.

- Monitor RPM and stabilize at desired reading.

- Throughout image capture execution, monitor oil temperature, RPM counter, and proper software execution.

- Remove air supply after capture sequence is complete and once rotor disk is at a safe rotation speed (<80 RPM) enter test bed facility and zero out control voltage to Oriel lamp.

8. Saving Wind-on Image

- Select "Image File Load/Save" from main menu save file as a TIFF format file (i.e. c:\4mip\images\xxx.tiff).

9. Wind-off Image Capture

The reference images (wind-off) are used to provide a reference intensity

condition for the wind-on image captured above. For the present work, wind-off images are referenced to static rotor conditions. Proper initial alignment of the rotor disk will facilitate proper post processing of images.

- execute image focusing procedures in step3 above (through image focusing step); rotate rotor disk until set-screw is centered around black marker on video monitor.

- Complete step 3

  - Disconnect 1/rev trigger from rotor disk and connect second Wavetek pulse function generator

  - Set pulse function generator frequency to the identical value as wind-on frequency to simulate wheel rotation.

- Increase line control voltage to Oriel lamp to 118% and select script AVGF.MPX execution file. File is identical to AVG.MPX with the exception of an execution time delay. Averaged image will be stored in image buffer 1.

- Select "Image File Load/Save" from main menu save file as a TIFF format file (i.e. c:\4mip\images\xxx.tiff).

10. Dark Current Image Capture

The dark current image captures the internal thermal noise of camera system. Dark current intensities are subtracted from wind-on and wind-off images to increase signal-to-noise ratios.

- Repeat procedure for wind-off image capture but with the lens cover attached to the camera to isolate noise intensities.

- Select "Image File Load/Save" from main menu and save file as a TIFF format

file (i.e. c:\4mip\images\xxx.tiff).

11. Post Processing

Processing of the captured images results in a single image of the ratio of wind-off to wind-on images. To increase the signal-to-noise ratio of the images, thermal noise generated within the acquisition system is subtracted from wind-on and wind-off images.

- Select "Load/Save Image" from the main menu; and load wind-on, wind-off, and direct images into image buffers 1,2, and 3 respectively.

- Select "Image Processing" from main menu and then "Two Image Arithmetic"; select "Subtract Images: PixB<- Abs(PixB-PixA)" from menu options.

The Subtract Images operation forms a single image from the difference of the corresponding pixels of two original images. PixA is the source image (dark current) and PixB is the image to be replaced (wind-on and wind-off images).

- Select image buffer 3 as the source (PixA) and select image 1 as the destination image buffer. Repeat procedure with image 2 as the destination image.

After image subtraction is complete, image buffer 1 and 2 should contain the noise-free images of the wind-on and wind-off images respectively. The final image ratio of wind-off image with respect to wind-on image forms the left hand side of the Stern-Volmer relation shown in Equation 1.

- Select "Image Processing" from main menu and then "Two Image Arithmetic"; select "Ratio Images: PixB <- (c0*PixB+c1)/(c2*PixA+c3)" where image buffer 1 (wind-on) is the source (PixA) and image buffer 2 (wind-off) is the destination (PixB).

- Change value for ratio coefficient, c0, to produce a usable image (values

between 20-80 will produce adequate image brightness). Large values of c0 will produce pixel intensity values of 255 and produce image blooming. Image buffer 2 will contain the final image ratio.

- Select "Image File Load/Save" from main menu and save file as a TIFF format file (i.e. c:\4mip\images\xxx.tiff).

12. Psuedo-coloring of Image Ratio

- Select "Load/Save Image" from the main menu and load final image into image buffer 1.

- From "Image Measurements" menu select "Histograms Displays"

- Select "Histogram - Horizontal (Linear & Logarithmic)" to display histogram of Pixel Frequency vs. Pixel Value. Determine the range of pixel values in which 90% of the data are located. The pixel value range determines the min/max values for image coloring. From Sievwright [Ref. 1] determine values for A,B,C,D, and E according the pixel value range. For example, an image where 90% of the data are located between pixel values 20 and 80 (A and B, respectively), the median value is 50, corresponding to position C, while the values for D and E can be varied, but usually have values closer to the median, such as 40 and 60, respectively.

- Select "Contrast and Lookup Tables" from main menu

- Select "Numerically Set & Show: Red Table"; and enter each segment of the Red, Green, and Blue tables corresponding to the values chosen for A, B, C, D, and E [Ref. 1]

- Select "Image File Load/Save" from main menu and save file as a TIFF format

file (i.e. c:\4mip\images\xxx.tiff). To save the color image select "Save LUT w. Image" option.

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